THE FUNDAMENTAL CYCLOTRON LINE IN 4U 1538−52

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Abstract: We present pulse phase averaged spectra of the high mass X-ray binary pulsar 4U 1538−52/QV Nor. Observations of this persistent accreting pulsar were made with the Rossi X-ray Timing Explorer (RXTE) .

We study the variability of cyclotron resonant scattering feature (CRSF or simply cyclotron line) in the high energy spectra of this binary system . We show that the parameters of the CRSF are correlated. The first one is, as suggested by theory, between the width and the energy of the cyclotron line. The second one is between the relative width (defined as σ_c/E_c) and the optical depth of the cyclotron line. We discuss these results with studies of other X-ray pulsars and their implications on the line variability.

Keywords: X-rays – Magnetic Fields – Accretion – Cyclotron Lines.

1 Introduction

X-ray binary systems are a perfect astrophysical laboratory to study the behaviour of matter and its interaction in extreme conditions of temperature, density, gravity and its magnetic fields. These physical properties are impossible to achieve in terrestrial laboratories. X-ray binaries are made up of a 'normal' (e. g. main sequence) companion star and a compact object. The compact object can be either a neutron star (NS) or a black hole (usually referred to as black hole candidate, BHC). Some of the observational evidence indicate that X-ray emission is generated by the accretion of material from the companion star onto the compact object. In these circumstances, matter falling onto a compact star releases gravitational potential energy, heats the matter and generates X-radiation.

In order to understand the emission properties of an accreting X-ray binary source, we need to know:

- the nature of the compact object, NS or BHC;

- the strength and geometry of the magnetic field, when the compact object is a NS;
- the geometry of the accretion flow from the companion to the compact object;
- the mass accretion rate;
- the mass of the system.

Taking the mass of the companion star into account, X-ray binaries can be classified into two main categories: High Mass X-ray Binaries (HMXB) and Low Mass X-ray Binaries (LMXB). These sources present a wide variety of phenomena, from quasi-periodic oscillations (QPOs) to X-ray outbursts. However, when binary systems contain a white dwarf (WD) and a low mass companion star, they are not called LMXB although X-ray emission is present. These sources are called Cataclysmic Variables (CVs) because they show very large variations in their brightness and are also fairly faint in X-rays.

Although there are some intermediate mass X-rays binaries (IMXB) (e.g., XTE J1819−254, GRO J1655−40, 4U 1543−475), in [1] they suggest that the majority of the LMXB systems may have descended from IMXB systems. There are some general books on X-ray binary systems as [2, 3, 4, 5] or reviews on this topic as [6, 7, 8] that can be useful to learn about X-ray astronomy. In the rest of this section we only consider HMXB systems.

In HMXB systems the companion is an O, B or Be type star with $M \geq 10\ M_\odot$ and the X-ray emission is produced by capture of material from the stellar wind by the compact object or through Roche-lobe overflow that can also be a supplement to the mass transfer rate in HMXB systems [2] (in Figure 1 we can see an example of both scenarios of mass transfer). Although the compact object in HMXBs may be a black hole, as in the case of Cyg X-1 (the first X-ray source discovered in the constellation Cygnus), they usually contain a NS .

Most HMXBs fall in one of the two main subgroups: those in which the primary has evolved away from the main sequence and becomes a supergiant (SG/X-ray binary) and those in which the primary has not reached the supergiant phase and is characterized by Balmer and HeI emission lines (Be/X-ray binary) .

In general, SG/X-ray binary systems are sources of persistent X-ray emission . At some stage of the binary evolution, the supergiant star ejects much of its mass in the form of a stellar wind; the NS can pick up some of these particles gravitationally and becomes a weak X-ray source. But, in the course of star evolution, another possibility may be an increase in radius of the companion star becoming a supergiant; then the outer layers of its envelope escape from the Roche lobe of the supergiant star through the internal Lagrangian point and becomes a bright X-ray source.

The most numerous class of HMXBs are Be/X-ray binaries, called also hard X-ray transients (see the catalog of [10]). The companion star is an Oe or Be star, which

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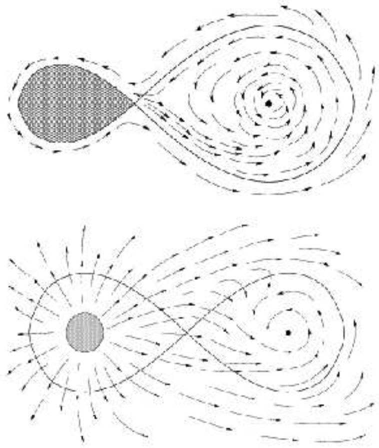

Figure 1: Mass transfer in a binary system. Top: When a massive star evolves the outer layers begin expanding and the star becomes a supergiant. If the star exceeds its Roche lobe, the material outside the Roche lobe is no longer gravitationally bound to the star. This material can now be captured by the compact object or expelled into the interstellar medium. Bottom: When the optical companion is an O or B star, the stellar wind can be very intense. Sometimes the compact object in a close orbit accretes material from the dense stellar wind and causes the weak X-ray emission [9].

are O or B stars with bright optical emission lines originated by circumstellar disc. It is believed that this envelope around the Be star is caused by its fast rotation. The orbit of the NS around the Be star is usually eccentric, so when is far away from the companion star cannot accrete material from this envelope. When the NS approaches periastron, it will be able to accrete material and the observer sees an X-ray outburst. Figure 2 shows a collapsed object in an eccentric orbit around a Be star (for a review of Be/X-ray binaries, [11, 12]).

However, a new kind of HMXBs was discovered by INTErnational Gamma Ray Astrophysical Laboratory (INTEGRAL) , called Supergiant Fast X-ray Transients [13], which are characterized by the occurrence of very fast X-ray outbursts. In [13] they have shown that at least a significant fraction of them are associated with supergiant stars.

Accreting X-ray pulsars were discovered by Giacconi et al. in 1971 [14] when they discovered the existence of periodic pulsations in the X-ray emission from Centaurus X-3. X-ray pulsars are rotating, highly magnetized NS accreting material from a companion binary star [15, 16, 17, 18]. Most known accreting X-ray pulsars belong

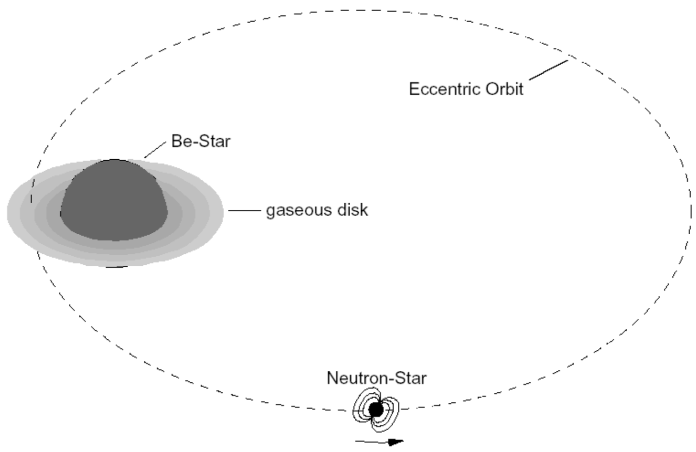

Figure 2: The NS revolves around the Be star in an eccentric orbit. When the NS comes inside the circumstellar disk of the Be star, accretion takes place and causes an X-ray outburst. However, while the NS is far away from the Be star, it is in quiescence and there is no X-ray emission.

to the HMXB class, such as 4U 1538−52/QV Nor. For accreting binary pulsars we measure their magnetic fields through the presence of cyclotron resonance scattering features (CRSFs) in their X-ray spectra because the cyclotron energy (E_{cyc}) and the magnetic field strength (B) are related to each other as $E_{cyc} = 11.6\ B(10^{12}\ G)\ (1+z)^{-1}$ keV, where z is the gravitational redshift.

2 Observational data

RXTE observed 4U 1538−52 between 1996 November 24 and 1997 December 13. To obtain the exact orbital phase we used the best fit orbital ephemeris from [19]. The exact time and the orbital phase are listed in [20].

In our analysis we used data from both RXTE pointing instruments, the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE). To extract the spectra, we used the standard RXTE analysis software FTOOLS.

The PCA consists of five co-aligned Xenon proportional counter units with a total effective area of $\sim$6000 cm^2 and a nominal energy range from 2 keV to over 60 keV ([21]). However, due to response problems above $\sim$20 keV and the Xenon-K edge around 30 keV, we restricted the use of the PCA to the energy range from 3 keV to 20 keV (see also [22]).

The HEXTE consists of two clusters of four NaI(Tl)/CsI(Na) Phoswich scintillation detectors with a total net detector area of 1600 cm^2. These detectors are sensitive from 15 keV to 250 keV ([23]). However, response matrix, instrument background and source count rate, limit the energy range from 17 to 100 keV. Background subtraction in HEXTE is done by source-background swapping of the two clusters every 32 s throughout the observation. In order to improve the statistical significance of the data, we added the data of both HEXTE clusters and created an appropriate response matrix by using a 1:0.75 weighting to account for the loss of a detector in the second cluster. We also binned several channels together of the HEXTE data at higher energies and chose the binning as a compromise between increased statistical significance while retaining a reasonable energy resolution.

3 X-ray spectral analysis

The X-ray spectrum in accreting X-ray pulsars has been investigated during the last two decades. Nevertheless, there still exists no convincing theoretical model for the continuum of this kind of sources ([24], and references therein). Therefore, we have to use empirical models of the continuum in the fitting process. In the RXTE energy band these models take the general form of a power law times an exponential above a characteristic cutoff energy.

3.1 Continuum model

We achieved a good description of the continuum X-ray spectra of this source using the standard pulsar continuum shape and customize models from XSPEC [20]. All of them are modified by a photoelectric absorption at low energies, a fluorescence iron emission line at 6.4 keV and the fundamental CRSF at 20 keV discovered by Ginga. The description of the continuum by physical models gave parameters that were not acceptable. We also modeled the observational data with several other standard pulsar continuum but they did not describe the spectra properly in the 7−16 keV energy band [25]. Therefore, in this paper we described the continuum produced in the accretion column of the NS by the Negative Positive power laws EXponential (NPEX) component modified by previous features. It was introduced by [26] and given by the formula:

$$NPEX(E) = A \cdot \left(E^{-\Gamma_1} + B \cdot E^{+\Gamma_2}\right) \cdot e^{-E/E_{fold}}\,, \qquad (1)$$

where Γ_1 and Γ_2 are positive and E_{fold} is the folding energy of the high energy exponential cutoff. We used a Gaussian emission line at ∼6.4 keV due to the fluorescence iron line and a multiplicative factor to fit the cyclotron line of the form:

$$cyclabs(E) = \exp\left(\frac{-\tau_c \cdot \left[\frac{\sigma_c \cdot E}{E_c}\right]^2}{(E-E_c)^2+\sigma_c^2}\right) , \tag{2}$$

where τ_c, σ_c and E_c are the optical depth, the width and the energy of the CRSF, respectively. We found that *cyclabs* model provides reasonable fits to the data. The observed X-ray spectrum of 4U 1538−52 is modified by photoelectric absorption due to the stellar wind of QV Nor.

3.2 CRSF variability

The main aim of this paper is to study the variation of the parameters of the cyclotron absorption line and their relations. The CRSF centered at ∼20 keV varies by ∼15% through the pulse [27]. In our pulse phase averaged spectra the parameter identified with the magnetic field, E_c, does not depend significantly on the orbital phase as is expected because it originates in the polar caps of the NS or the accretion column where the X-rays and the pulse forms [20]. In fact, the energy of the CRSF only varies by ∼4% (in some cases the same that the uncertainties of the parameter at 90% confidence level). Therefore, the stellar wind does not modify the accretion onto the NS during an orbital period significantly. However, we found that the relative width of the CRSF and its optical depth are correlated, as well as the CRSF energy and its width .

Although pulse phase resolved spectroscopy allows us to study the variation of the pulsar emission over the X-ray pulse, it seems that the correlations between the parameters of the CRSF are indeed real in pulse phase averaged spectroscopy. Using a consistent set of models [28] Coburn et al. parameterized a large sample of X-ray pulsars observed with RXTE which exhibit cyclotron lines. They found a new correlation between the relative width of the CRSF, σ_c/E_c, and its optical depth, τ_c. Although they used pulse phase averaged spectra, another study of GX 301−2 [29] with pulse phase resolved spectra confirmed this correlation. They also reported another correlation between the cyclotron line width and the energy of the cyclotron line, both in pulse phase average and resolved spectra. Therefore we have plotted our fitted results for the cyclotron line parameters to check these correlations.

In Figure 3 we show the first correlation between the CRSF parameters in the $\sigma_c - E_c$ plot. For a self-emitting atmosphere, the cyclotron line width and his energy is given by [30]:

$$\sigma_c \approx E_c \left(8 \ln 2 \frac{k\,T_e}{m_e\,c^2}\right)^{\frac{1}{2}} |\cos\theta| , \tag{3}$$

where $k\,T_e$ is the temperature of the electrons along the magnetic field lines, E_c the cyclotron line energy, and θ the viewing angle with respect to the magnetic field.

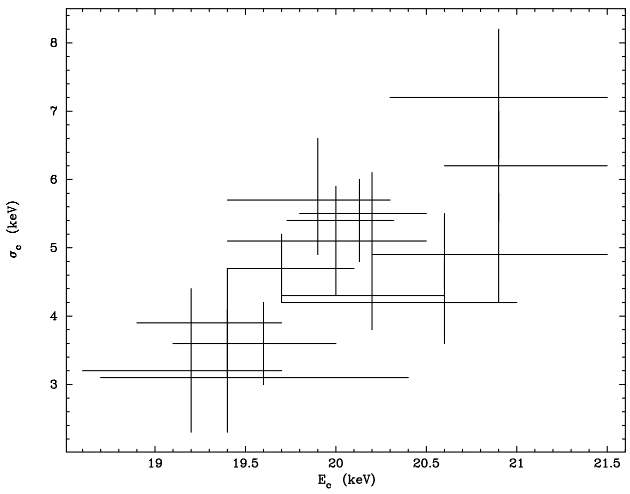

Figure 3: CRSF width σ_c versus CRSF energy E_c in 4U 1538−52. Note the moderate correlation between them. The bars indicate the uncertainties at 90% confidence level.

Therefore a linear correlation is only possible if $\cos\theta$ does not change significantly. Our results imply an angle close to zero when $k\ T_e$ is 5.2 keV and can take a value of 18^o if the energy of electrons is 5.8 keV.

The parameter E_{fold} in the NPEX model is the typical temperature of the X-ray emitting plasma in keV. Basic Comptonization theory suggests that $k\ T_e$ can be estimated from the folding energy of the pulsar continuum. Furthermore, if we assume that the seed photons for the Compton scattering in the accretion column are created throughout the volume of the accretion column, then detailed Monte Carlo simulations show that the optical depth of the CRSF is expected to be largest when the line of sight is almost perpendicular to the direction of the magnetic field [31]. If the temperature in the accretion column is constant, these models predict an anti correlation between the optical depth and the relative width of the CRSF. As we show in Figure 4, our phase averaged spectra results for 4U 1538−52 indicate a moderate correlation opposite to the models, and the conclusion is that the temperature in the accretion column is not constant. This correlation indicates that as CRSF increase in optical depth , the CRSF relative width increases as well.

In the above discussion, it has been assumed that the X-ray emission is produced from one homogeneous emission region. However, this source has contributions from both magnetic polar caps, which could influence the observed correlation. In fact, in 4U 1538−52 the two polar caps are observed and are unequal and non antipodal [32].

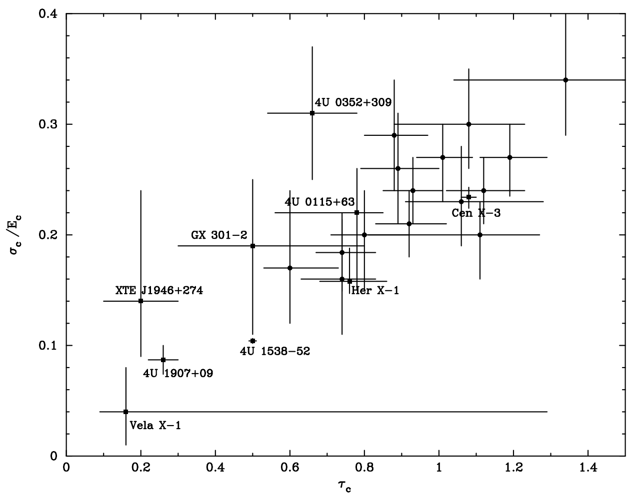

Figure 4: Fractional CRSF width σ_c/E_c versus the optical depth of the CRSF for several accreting pulsars from RXTE. Filled squares: values derived by [28] from phase averaged spectra. Filled circles: values derived from phase averaged spectra for 4U 1538−52 (this work, the bars indicate the uncertainties at 90% confidence level). All quantities refer to the pulse phase averaged values. Note the moderate correlation between them.

Therefore we can expect the parameters of the X-ray continuum emitted by each pole to be different, which can be reflected by changes in the observed continuum parameters. The variation in the folding energy of this system could explain this correlation caused by a mixture flux from the two polar caps. However, this reason cannot be the only one because, for example, in GX 301−2 the folding energy does not change significantly [29].

Assuming that equation 3 is correct and $\cos\theta$ does not change appreciably, we expect a relationship between the folding energy and the relative width of the CRSF. As we can see in Figure 5, we found that the relationship was consistent with a power law $\sigma_c/E_c \propto E_{fold}^{0.5}$, indicating little variation of the angle θ and according to equation 3. However, the statistic of the data is such that, from Figure 5, we cannot distinguish between the last relationship and a linear correlation $\sigma_c/E_c \propto E_{fold}$, at a statistically significant level.

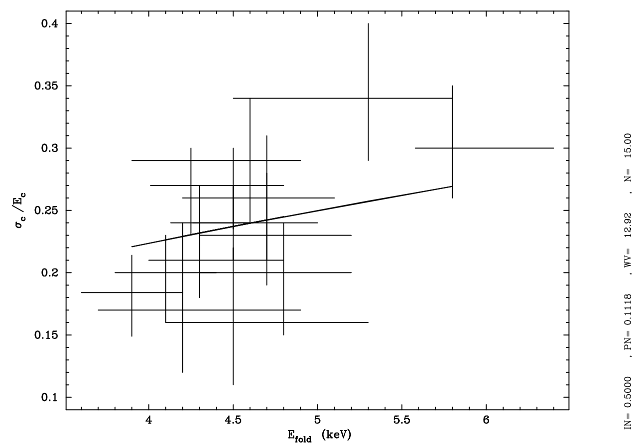

Figure 5: Fractional CRSF width σ_c/E_c versus the folding energy. All quantities refer to the pulse phase averaged values. The bars indicate the uncertainties at 90% confidence level.

4 Summary and conclusions

We have studied the variability of the parameters of the fundamental cyclotron absorption line in the HMXB 4U 1538−52. In order to explain this variability, we have also studied the relationship among the continuum (E_{fold}) and cyclotron line parameters.

As shown in Figure 4, our pulse phase averaged results for 4U 1538−52 are in agreement with the correlation found by [28]. Also the pulse phase resolved results for GX 301−2 [29] noticed the same correlation, so it suggests that it is not due to effects of averaging. In terms of the relativistic cross sections, this result is in the opposite sense.

Furthermore, the fundamental CRSF of this source has a width nearly proportional to its energy. If we consider only a thermal broadening, then the variation of the viewing angle is not significant.

Our third result is a relationship between the folding energy $E_{fold} = k\, T_e$ and the relative width of the cyclotron line. Figure 5 shows this correlation and it implies viewing angle close to zero which is consistent with the previous correlation.

Our results for the spectral analysis of the RXTE data of 4U 1538-52 can be summarized as follows:

- The absorbed NPEX continuum model provides a reasonable description of all the spectra used in this research. It approximates a photon number spectrum for an unsaturated thermal Comptonization in a plasma of temperature T_e.

- The correlation between the width of the fundamental CRSF and its energy suggests little variations of the angle between the line of sight and the magnetic field in the accretion column.
- The relationship between the folding energy and the relative width of the fundamental CRSF implies that $\cos\theta$ is close to 1. As an example, $\cos 26^o \sim 0.9$, so a little variation of the viewing angle and its relationship is consistent.
- The correlation between the relative width of the cyclotron line and its optical depth implies changes in the angle between the line of sight and the magnetic field at the NS poles, but in the opposite sense to the numerical simulations for the optical depth of the line.

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